

## Description

# SYSTEMS AND METHODS OF ALTERING A VERY SMALL SURFACE AREA

### CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The following applications (International Business Machines Corporation) are related to the present application: US Patent Application No. 10/261275, filed September 30, 2002, titled "Tool Having a Plurality of Electrodes and Corresponding Method of Altering a Very Small Surface," and Attorney Docket No. FIS920020170US1, titled "System and Method of Altering a Very Small Surface Area By Multiple Channel Probe." The disclosures of these applications are incorporated herein by reference.

### BACKGROUND OF INVENTION

[0002] Current repair processes for integrated circuit (IC) chips and lithographic reticles rely primarily on the use of focused beams (ion, electron, and/or photons) to induce localized reactions for etching or deposition of materials for when editing patterns. Focused Ion Beam (FIB) tools have

played a dominant role for most repair applications as well as in failure analysis methods, due to their superior spatial process confinement and reaction rates (relative to scanning electron or photon beams). However, concerns about energetic ion beam induced damage and contamination have severely limited the applicability of FIB tools inside IC clean rooms and lithographic mask production facilities. The more recent use of non-legacy materials, such as copper metallization and low-K dielectrics (polymers) in IC fabrication has also raised concerns about the extendibility of present FIB technology for these applications.

[0003] Figure 1 illustrates such example, which is background to the invention, but is not admitted to be prior art. As shown in Figure 1, a copper feature 10 of a substrate 20 lies under a plurality of layers 12 of inter-level dielectric (ILD) material. Specifically, the editing (i.e. cutting) of lower level metallization copper IC features 10 by FIB tools has proved troublesome due to the tendency of the copper milled by the tool to be redeposited on surfaces 14 of the entry hole 16 made by the tool (focused beam 15). Regions 11 where the copper remains or is redeposited are conductive and thus, the desired degree of electrical

isolation (i.e. the reason for cutting the line) is not achieved. In addition, when ILD 12 is an organic-based low-K polymer, it may become conductive in places 14 which are exposed to an energetic ion beam 15.

[0004] In addition, changes in the optical properties of litho-graphic masks, known as staining, caused by gallium ions (the source of ions in FIB tools is Ga+) and edge streaking (river-bedding) are examples of problems being encountered with FIB- based mask repair. In addition, there are no suitable beam induced chemistries for complete volatilization of chrome (of which opaque mask features are made) etch products. This forces one to rely on mostly physical sputtering with the ion beam to edit chrome mask features, which dramatically increases the amount (dose) of gallium to the mask surface and hence staining (i.e. lower optical transmission as well as phase error). Thus, a critical need exists for a new tool and method for the working of micro-scale surfaces, for example, for the repair of IC's and masks. At the same time, the failure of existing in-line metrology techniques to provide accurate three dimensional data for the development and control of IC fabrication processes has highlighted the need for a tool capable of sectioning a surface without causing dam-

age or contamination (Ga+ is a metal) to either the surface or to clean room equipment and materials.

[0005] Scanning of focused laser beams has been used to induce spatially localized chemical reactions to pattern various surfaces. In such processing, chemicals needed for the reaction are activated either directly by photolytic excitation, or indirectly through conversion of photons into thermal energy. As shown in Figure 2A, a spot of light 22 is created at a desired site of a reaction by focusing a beam 24 with conventional far-field optics. The spatial extent of the reaction is confined by the size of the beam spot 22 on the surface. In many cases, pulsed laser beams can be used to directly ablate material from the surface without any chemical reactants. This occurs when the laser beam energy is focused to within a small enough region spatially for achieving higher density at the target surface and delivered within a very short time span (i.e. pulsed), so that the material under such exposure conditions will thermally evaporate. Selectivity is still achieved due to the large difference in optical absorption and thermal properties between chrome features and quartz mask substrate materials.

[0006] However, as shown in Figure 2B, diffraction of the beam

through focusing mechanisms constrains the minimum dimension (focal spot) 26 at which the beam spot may be formed. Patterns are created on a surface by controlling the scanning of the focused laser beam spot across the surface. While laser beam processing can support reaction rates generally higher than that of FIB and electron beam, the inability to spatially confine the reaction below the diffraction limit of the beam poses a serious challenge to its use. Another disadvantage of laser beam processing is the need to flood the sample surface and possibly the entire process chamber with gases needed to support the reaction. With the reaction-supporting gases extending well beyond the desired reaction site, only endothermic reactions can be confined, because only such reactions do not spread beyond the energy source, i.e. the beam.

Aberrations and diffraction effects also limit the minimum spot sizes for focused ion and electron beams, as well. A serious disadvantage common to all existing beam techniques is the inability to confine the energy vertically (i.e., along the axis of beam propagation) as well as the inability to sense, in real-time, the actual surface height during the modification process. This capability is very important when editing three-dimensional structures, such as

phase-shifting mask features.

[0007] Near-field scanning optical microscopy (NSOM) is a technique which permits imaging at a spatial resolution below the diffraction limit of the illuminating source. This technique involves imaging with evanescent optical modes, either by intensity collection, or by illumination through a sub-wavelength aperture placed at the apex of a scanned light guide or probe. In this technique, the apex of the light guide or optical probe (acting as source, collector or both) is brought very near the sample surface (typically using SPM instrumentation) to create a localized spot of light. Super resolution optical imaging is achieved beyond diffraction limits, because lenses are never used to focus the light.

[0008] For inducing localized chemical processes with near-field optical photons, a scenario involves illumination by an uncoated light guiding probe. Light 39 is guided inside the probe 28 by total internal reflection until it reaches the tapered region, and escapes 33, as shown in Figure 3A, then impinging as a spot 34 on the surface. Chemicals adsorbed on the surface are then activated by the light, which escapes from the tapered waveguide region. This is similar to the light distribution from an uncoated optical

fiber probe in shear-force microscopy. Although simple, this approach would result in fairly poor lateral resolution (at least hundreds of nanometers).

[0009] Alternatively, one or more chemicals needed for a reaction can be supplied through a hollow channel of a light guiding probe, to spatially localize the reaction to the extent the chemical(s) is distributed from the probe, as in a localized chemical delivery probe technique. As shown in Figure 3B, an optically opaque coating 36 can be applied to sidewalls of the light guiding probe 29 to prevent light 37 from escaping before reaching an aperture 32 contained at the apex. The aperture can be made very small, diameters of 20 nm having been reported. When the aperture is much smaller than the wavelength of propagation of the light guide, only evanescent near-field optical (NFO) modes 35 pass through the aperture.

[0010] To promote a localized reaction on a surface, chemicals at the location are exposed by near-field optical (hereinafter "NFO") light emanating from the aperture. Since the NFO light spatially confines the reaction in some measure, chemicals can be supplied as an ambient, nozzle injected for surface adsorption, or locally through a hollow light guiding localized chemical delivery probe (LCDP). While

NFO light guiding probes appear to spatially confine photochemical processes better than the other described techniques, their feasibility for repair and metrology is still problematic for many reasons, primarily: (a) it is difficult to fabricate consistently high quality nanometer scale NFO probe apertures; (b) maximum intensity output is limited to aperture size; (c) apertures are more susceptible to thermal and mechanical damage than solid tips; (d) optical absorption by the metal coating generates heat which can delocalize chemical reactions; (e) the conical shape of the probe limits the aspect ratio of the sample topography that can be scanned; and (f) resolution for imaging and processing in the lateral dimension is limited (e.g., 20nm).

[0011] Thus, there is a need for improved methods and tools for altering features at small scale (e.g.,  $\mu\text{m}$  or  $\text{nm}$  scale) while avoiding undesired side effects such as contamination, undesired byproduct re-deposition, undesired thermal ablation and/or undesired mechanical ablation. There is also a need for tools capable of such process which are highly maneuverable, relatively inexpensive and wear resistant. There is also a need for real-time monitoring of 3D surface topography for end-pointing etch/deposition modification processes.

## SUMMARY OF INVENTION

[0012] The invention provides methods and systems for altering a features on a substrate (especially micron-scale or nanometer-scale features, e.g., such as found in an integrated circuit or photomask). The methods of the invention are characterized by highly localized delivery of a chemical and/or activating energy to the site of the target feature whereby the chemical reaction and/or mechanical milling associated with the alteration is substantially confined to the site. The systems of the invention are characterized by the presence of a chemical source and an energy source wherein at least one of the two is capable of highly localized delivery.

[0013] In one aspect, the invention encompasses a method for altering a surface feature of an existing pattern on a substrate, the method comprising: (a) delivering a chemical to a site proximate to a target feature to be altered, and (b) providing activating energy at the site whereby a chemical reaction and/or milling occurs, wherein the chemical delivery and/or the providing of energy occurs only locally at the site whereby the chemical reaction and/or milling occurs only locally to the site, the reaction and/or milling resulting in alteration of the feature. Preferred methods of

local chemical delivery are (i) by passing the chemical through a probe tip channel having an opening placed proximate to the site or (ii) by placing a probe tip coated with the chemical proximate to the site. A preferred method of non-localized chemical delivery is by providing a fluid containing the chemical at the site (e.g., as a fluid flow or as part of the environment in the tool.

[0014] Preferred methods of delivering activating energy is provided by illuminating a probe tip proximate to the site. In one embodiment, the probe comprises a non-metal portion and a metal apex portion which causes localized scattering of photons at the site. In another embodiment, the probe tip comprises at least two electrodes with a gap there between and the activating energy comprises coherent radiation at two wavelengths whereby interaction between the electrodes and activating energy causes formation of a plasma between the electrodes. The method activation energy is preferably provided by directing far-field energy selected from the group consisting of light, electron beam and ion beam.

[0015] In another aspect, the invention encompasses a system for altering a surface feature of an existing pattern on a substrate, the system comprising: (a) a probe maneuver-

able to a site proximate to a target feature to be altered, (b) a chemical source being adapted to provide delivery of a chemical to the site proximate to a target feature to be altered, and (c) an energy source for providing activating energy at said site, wherein the chemical source is capable only of local chemical delivery and/or the energy source is capable of providing of energy only locally at the site. The energy source is preferably a source of far-field energy selected from the group consisting of light, electron beam and ion beam. The chemical source preferably comprises a channel in the probe for delivering the chemical, or a component from which at least a tip of the probe is made. In one embodiment, the probe comprises a non-metal portion and a metal apex portion which causes localized scattering of photons at the site. In another embodiment, the probe tip comprises at least two electrodes with a gap there between and the activating energy comprises coherent radiation at two wavelengths whereby interaction between the electrodes and activating energy causes formation of a plasma between the electrodes.

[0016] The site of the target feature is preferably to dimensions of about 10  $\mu\text{m}$  in diameter to as small as 0.01  $\mu\text{m}$  or smaller. The system and method are preferably applied to

the repair and/or metrology of very small features of densely patterned substrates, e.g., an integrated circuit, package, reticle or photomask.

- [0017] These and other aspects of the invention are described in further detail below.

#### **BRIEF DESCRIPTION OF DRAWINGS**

- [0018] Figure 1 illustrates a background method of etching a substrate using a focused ion beam (FIB) tool.
- [0019] Figures 2A, 2B illustrate optical diffraction limitations on resolution for photo- chemical processing.
- [0020] Figures 3A and 3B illustrate background methods for altering a substrate using energy guiding probes.
- [0021] Figures 4A, 4B and 5 illustrate systems and methods according to a first group of embodiments of the invention.
- [0022] Figures 6 and 7 illustrate systems and methods according to a second group of embodiments of the invention.
- [0023] Figures 8A and 8B graphically illustrate principles of the invention to facilitate local generation of a micro-plasma at the apex of a probe by mixing of light optical wavelengths.
- [0024] Figures 9 –10C illustrate embodiments of probes used to generate micro-plasma.
- [0025] Figure 10D illustrates an embodiment including an array

of micro-plasma generated probes.

[0026] Figure 11 illustrates a preferred embodiment of a system including a probe for altering a very small surface area on a substrate.

## DETAILED DESCRIPTION

[0027] The invention provides methods and systems for altering a features on a substrate (especially micron-scale or nanometer-scale features, e.g., such as found in an integrated circuit or photomask). The methods of the invention are characterized by highly localized delivery of a chemical and/or activating energy to the site of the target feature whereby the chemical reaction and/or mechanical milling associated with the alteration is substantially confined to the site. The systems of the invention are characterized by the presence of a chemical source and an energy source wherein at least one of the two is capable of highly localized delivery.

[0028] A method of activating reactions to alter a very small surface (as by milling, etching and/or depositing) with assistance of far-field illumination will now be described. As shown in Figure 4A, in a first preferred embodiment, far-field illumination 40 is supplied to a desired reaction site 42 on a surface of a substrate 44 (e.g., IC, component,

package, photomask, reticle, etc.). Also supplied thereto is one or more chemicals 46 (gas, liquid, or both) to assist the reaction from an output aperture 48 of a localized chemical delivery probe (LCDP) 50. One or more other chemicals 52 for supporting or assisting the reaction may also be supplied as an ambient or through directed flow to the desired reaction site. A chemical 46 is provided to the reaction site 42 through a channel 50 in such probe, and occupies only a very limited area including the desired reaction site. Far-field illumination 40 is then supplied to promote creation of a reactive species. Etching or deposition on the surface is then promoted by the induced reaction. The reaction is spatially confined because the LCDP probe spatially limits the distribution of the reaction-supporting chemical. Because the reaction is spatially confined by the extent of chemical distribution, the extent of the far-field illumination may be broader than the extent of chemical distribution.

[0029] In a further preferred embodiment, the method of the invention may be used to support deposition of a light sensitive polymer to the reaction site 42. In such case, an opaque coating 54 is preferably applied to the sidewall of the probe 50 so that a polymer dispensed to the reaction

site 42 through probe 50 does not begin curing prior to exiting aperture 48.

[0030] In another preferred embodiment, as illustrated in Figure 4B, a solid probe LCDP having a tip 60 is used to provide highly localized delivery of a chemical to assist in a reaction to a site proximate to the target feature. Such solid probe LCDP can be fabricated from a variety of materials (e.g., from one or more metals, silicon, glass, a polymer, etc.) such as needed for the particular application. A chemical for assisting in the reaction may be provided as a component material of at least a tip 60 of the solid probe, or alternatively, carried in liquid phase or solid phase form as a coating 62 applied to tip 60. Solid coatings 62 may be applied to the tip 60 by sputtering or evaporative deposition, or other suitable technique. The coating 62 may include a chemical which, when activated, provides a reactive species. Alternatively, or in addition thereto, a chemical of the coating 62 may be a catalyst for the desired reaction. When the coating 62 supplies only a catalyst, a second chemical is preferably distributed to the site in a less localized manner, e.g., as by chemical ambient or as a generalized flow directed toward the surface. Preferably, the highly localized delivery of such chemical

spatially confines the reaction to dimensions smaller than the diffraction limit of the activating energy source.

- [0031] If desired, the chemical may be carried by tip 60 by dipping the tip 60 into a source of the chemical, and then carrying the wetted tip 60 to the site proximate to the target feature where activation energy is present. In another variation, a solid probe having a wet liquid chemical layer on the tip 60 slowly releases the chemical to the surface of the tip, as by the flow of a small quantity of a liquid chemical from a reservoir (not shown) above the apex slowly down to the apex in a quantity which spatially confines the reaction.
- [0032] The activating energy may act directly and/or indirectly (by causing surface heating at the target site) to activate one or more chemicals to support or assist in the desired reaction. Direct activation provides better spatial localization and/or control, while surface heating may permit a higher reaction rate. In a preferred embodiment of the invention, tuning of reaction rate vs. confinement may be possible through adjustment of activating energy source properties, e.g., by selecting the focusing and/or intensity properties of the activating energy source (e.g., far-field illumination) to fit the need at hand.

[0033] Figure 5 illustrates a system for repair/editing a surface of a feature of a pattern on a substrate. A substrate 510 containing the feature to be edited rests on a movable stage 512 for initial coarse positioning of the substrate 510 and optical navigation under a high-NA (numerical aperture) objective lens microscope 514 to surface 520. High NA optical microscope viewing/ imaging allows one to see where the tip 516 of the probe tool 518 is relative to the feature to be edited on the substrate, even if the feature to be edited is below surface 520 (e.g., when the substrate includes one or more optically transparent layers above the feature of interest). The separation between the tip 516 and surface 520 is then actively regulated via surface force feedback (from transducer 522) and control electronics 524. In a preferred embodiment, a reservoir source of chemical 528 is coupled through one or more ducts 530 for supplying the fluid by the probe tool tip 516 to the surface 520. Preferably, the duct(s) 530 provide chemical to a channel of probe tool 518 such that the location of chemical delivery to the substrate 510 is controlled in connection with the above-described method for positioning the tip 516 proximate to the site of the target feature.

[0034] In a preferred embodiment the tip 516 may include transparent guiding means 540 coupled to a source 550 of activating energy (e.g., far-field illumination) to the site at surface 520. Alternatively, far-field illumination may be provided externally to the body of the probe 518 by an illuminating source 560, outputting a focused beam of light, electron beam or ion beam to the site at surface 520.

[0035] In a preferred embodiment, a system may be adapted for a particular application, such as the repair of a copper feature on an IC, which may be buried beneath one or more layers of inter-level dielectric (ILD). In such case, the system may include multiple probe tools, e.g., a first probe tool having a tip adapted to etching the ILD above the copper feature, and a second probe tool having a tip adapted to editing the copper feature. In such case, the ILD can be selectively etched out, leaving existing metal patterns, by the first probe tool in which the reaction may be promoted over a somewhat larger area of the IC (e.g., 5 to 50 times larger diameter) than the area in which the second probe tool subsequently edits the copper feature. When the second probe tool edits the existing copper feature, any copper redeposited thereby (as a byproduct of

the editing process) is distributed in very small amounts over a large area. Consequently, any redeposited copper is much less likely to form deposits which are attached and continuous, such as could cause conductive shorting of exposed metal patterns.

[0036] In another preferred embodiment, a system as in Figure 5 may be used to repair of a transmissive defect in a photomask (a feature of a mask which shifts the phase of the light transmitted therethrough and/or attenuates the light). Such defects occur in the clear (light transmissive) portions of the mask, rather than in opaque features, e.g. the chrome patterns of a mask. A system as shown in Figure 5 is particularly adapted to the repair of transmissive defects in masks because the reaction used in the repair can be spatially confined by the extent of chemical distribution provided by the probe 518 where probe 518 is an LCDP. Thus, the highly localized chemical delivery limits the repair to only the desired location and depth.

[0037] In a second group of embodiments, activating energy is introduced to the site of interest, by far-field illumination onto the apex of a probe, where the apex has properties that stimulate near-field scattering to produce highly localized energy at the reaction site. Far-field illumination

that is not scattered by the near-field enhancement effect of the probe tip apex, may nevertheless assist in the reaction by imparting thermal energy to the reaction site, such as may assist in promoting the rate of the reaction and the removal of subsequent products.

[0038] Figures 6 and 7 illustrate embodiments using near field scattering. Polarized light 610 from a far-field source (e.g., a laser), external to the probe body 630 is focused onto a metal scattering object 620 on the apex of a probe 630 in close proximity to a reaction site 640 on a surface of a substrate 650. Such far-field illumination preferably includes one or more wavelengths selected from range consisting of the infrared to the ultraviolet. Enhancement of the near-field energy results when the diameter of the metallic scattering object 620 is made smaller than one tenth of the wavelength of the far-field illuminating source 610. Further enhancement of the field can be achieved if a material discontinuity is introduced at the apex, such as when the scattering object 620 is metallic and body 630 of the probe is a nonconductor (e.g., glass) or semiconductor (e.g., silicon). Thus, far-field illumination onto the metal scattering object 620 in close proximity to the reaction site 640 invokes highly localized en-

hancement of the electromagnetic field 660. The incident far-field illumination 610 also provides a background spot of far-field intensity 670 around the highly localized enhanced near-field 660 region. The near field scattering preferably acts to perturb the energy level at a very specific point above that which is required for the chemical process to begin. The chemical (gas, liquid, or both) 615 can be introduced as an ambient, directed towards the reaction site 660 by nozzles onto the surface, or through a hollow channel of the probe body.

[0039] Examples of hollow LCDP probes and solid, chemical-coated LCDP probes are shown in Figures 7A and 7B, respectively. In such probes, a chemical for promoting the reaction is delivered, in a highly localized manner, to the reaction site 720 either through a channel 730 inside the probe, or as a solid phase chemical or liquid phase chemical carried as a coating 722 on the surface of a solid probe. A solid LCDP probe, not having an interior chemical channel, can be fabricated from a variety of materials (e.g., metals, silicon, glass, a polymer, etc.) as needed for the particular application.

[0040] The metal electrode 710 of the probe shown in Figure 7A and electrodes 712, 714 of the probe shown in Figure 7B

at the LCDP apex region act as apertureless near-field optical scattering objects with which to enhance the near field energy. As illustrated in Figure 7B, further enhancement of the near field energy may be possible if the electrodes 712, 714 of the probe, are closely spaced to form a dipole and placed in close proximity to the desired reaction site 720. If desired, when deposition or etching of large areas is desired, one can increase the background energy level of the far-field illumination 770 above the reaction threshold to essentially perform laser beam based processing.

[0041] A third group of embodiments of the invention employ localized plasma generation as shown in Figures 8A and 8B. In Figure 8A, a micro-plasma is generated by the mixing of two different wavelengths (i.e., two different frequencies) of coherent radiation (e.g., laser light) at the apex of a probe in close proximity to a highly localized site of interest 820. A plasma can be sustained when an inert gas and/or a reactant is present. Reactive species can be produced locally when a chemical (gas, liquid or both) is provided to the surface of the sample, either by local distribution to the probe apex or in the ambient. Proximity of the plasma source 810 to the sample surface is then de-

terminated by control of the probe position. Due to the probe having gapped electrodes which establish and control the position of the plasma, the plasma is established at the probe apex 816 regardless of the probe's proximity to the sample. If desired, a DC bias can be applied to the substrate in order to accelerate the generated reactive species towards the substrate surface.

[0042] Open electrodes (not shown in Figure 8A or 8B) are located in the apex 816 of the probe 818. The electrodes generate a plasma when coherent radiation of at least two different frequencies is provided thereto and a fluid (e.g. inert gas and/or reactant) is present. The electrode gap has a nonlinear, exponential current transfer function, not unlike that of a forward-biased semiconductor diode. In other words, the output current of the gapped electrodes is an exponential function of the voltage which is input thereto. When coherent radiation at two different frequencies is provided to the gapped electrodes, the two wave functions are multiplied together, analogous to the frequency mixing which occurs in a tuner of a radio receiver. The mixing process results in output at two dominant frequencies: one frequency at the sum of the two different input frequencies, and a second one being at the differ-

ence between the two different input frequencies. It is the second, difference frequency, obtained by the exponential transfer characteristic of the gapped electrodes that provides an oscillating electric field for generating a plasma at apex 816 of probe 818. Tuning the difference between the radiation frequencies can produce radio and/or microwave radiation, such frequencies being preferred for plasma processing. The RF/microwave radiation is then used to ionize various gas species to create a plasma. Localization to a confined micro-plasma volume at the probe apex is accomplished by choice of tip electrode geometry. Preferably, the micro-plasma volume is not quite as wide as the separation between the electrodes in the probe apex, due to sheath regions.

[0043] Referring to Figure 8B, a desired density of electron current 830 is established in close proximity to the reaction site on a surface of the substrate 835 by irradiating the probe apex with two different frequencies of coherent radiation 831, 832 (e.g. laser, maser, or coherent radio frequency). Molecules of an inert gas or reactant gas are introduced to the volume surrounding and including the probe apex (not shown). When the gas provided is an inert gas, e.g. argon, the highly localized plasma 834 can be

used to mechanically mill a very small surface area in close proximity to the probe. When the gas provided is a reactant, the highly localized plasma confines the desired reaction to the region of the substrate in close proximity thereto, due to the short lifetime of the reactive species.

[0044] A first plasma probe of the third group of embodiments is illustrated in Figure 9A. Tip 900 of the probe has a diameter on the order of 1 mm or less, and includes a first electrode 910 and a second electrode 920, which are open, i.e., not in conductive contact with each other or any other conductor at the apex 930. A insulator 940 separates the first electrode 910 from the second electrode 920. In this embodiment, first and second electrodes 910, 920 are coaxial, first electrode 910 having a smaller diameter and arranged concentrically inside second electrode 920. First and second electrodes 910, 920 have a gap between them which is preferably about 3 microns to as small as 0.01 microns or less. This spatial arrangement produces an electron current which is radially symmetric. At apex 930, first electrode 910 extends beyond second electrode 920. This arrangement produces an electric field having lines of electric flux extending into the volume near apex 930 outside of tip 900.

[0045] Figure 9B illustrates a variation of this embodiment in which first electrode 911 at apex 932 is recessed relative to second electrode 921. In this variation, more of the lines of electric flux remain within cavity 934 within tip 901, and less remain outside of tip 901. First and second electrodes 911, 921 are configured in such manner that lines of the electric flux are oriented in generally lateral direction (i.e., not at a high angle thereto) thereby assisting vertical confinement of the reaction. Preferably, apex 932 is coated with one or more protective layers to prevent damage to tip 901 if particularly aggressive chemical processes are to be induced.

[0046] Figure 9C illustrates a further embodiment of a plasma probe. In this embodiment, the tip 950, of diameter on the order of 1 mm or less, has two parallel electrodes 952 and 954, respectively. As in the previous embodiment, electrodes 952 and 954 are open, that is, not in conductive contact with each other or any other conductor at apex 956. Insulative material 957 helps mechanically support electrodes 952, 954 while insulating them from each other and unwanted contact with an external conductor. First and second electrodes 952, 954 have a gap between them preferably similar to the gap for the first plasma

probe described above.

[0047] Figure 9D illustrates another plasma probe embodiment having a tip 960 of diameter on the order of 1 mm or less in which first and second electrodes 962, 964 are arranged in parallel, but also arranged in arc fashion over an underlying insulator 966 of tip 960. The gap between first and second electrodes 962, 964 is preferably similar to the gap for the first plasma probe described above. Fabrication of tip 960 may be simplified. For example, an insulator 966 can be coated with a conductive film, and the conductive film then etched in two lines extending down tip 960 to apex 968 from two open electrodes 962, 964.

[0048] Figure 10A illustrates yet another probe embodiment having a tip 1000 which includes not only first and second open electrodes 1010, 1020, but also one or more channels 1030 for delivering a fluid or gas to the apex 1002. An insulator 1004 separates the open electrodes 1010, 1020 from each other, while also helping to mechanically support them and hold them in relation to each other. The channel(s) 1030 delivers a fluid reactant to apex 1002. The fluid which may contain one or more chemicals helpful in assisting the reaction or controlling it.

[0049] Figure 10B illustrates another embodiment in which the

center electrode has tip 1040 and an open volume 1050 which are recessed within outer electrode 1010.

- [0050] As an alternative to delivering a reactant chemical via a channel 1030 of the probe tip 1000, tip 1000 may form a solid type LCDP probe, including a solid chemical or chemical coating 1035 for assisting in the reaction.
- [0051] In another embodiment (Figure 10C), a plurality of tools, constructed according to the third group of embodiments, are arranged in an array 1060. The array may be brought into close proximity to a substrate surface 1062, such that a larger area of the substrate can be modified (e.g., repaired) simultaneously. For providing the two different coherent radiation frequencies, two different narrowband sources may be used (e.g., lasers). Alternatively, a single source arranged in an interferometric configuration may be used to provide coherent radiation simultaneously at two different frequencies.
- [0052] Possible configurations for providing the coherent radiation to the gapped electrodes include: (i) laser light from uncoated fiber/capillary core, (ii) focused spot from a far-field objective lens, (iii) combined optical fiber and objective lens; and (iv) near-field aperture of a coated, light guiding probe.

[0053] A plasma is established and sustained between electrodes at the probe apex while the fluid (inert or chemical reactant) is introduced and activated. Mechanical milling, etching and/or deposition then occurs if the probe is brought into sufficient proximity of the target surface. Protective coatings can be added near the tip of the probe to protect the probe body from the particular chemical process induced. The farthest protruding electrode is preferably grounded, so that incidental contact with the substrate will not cause electrical shorting on conductive surface regions. In some instances, however, it may be desirable to use shorting to terminate the process on conductive features. The electrodes are preferably configured such that the current density only has lateral components, therefore achieving extreme vertical confinement (i.e., along the probe axis direction). A small enough electrode separations, tunneling currents (instead of field emission) can be used for inducing plasmas. Utilization of tunneling currents further improves spatial confinement of the chemical reaction in three dimensions.

[0054] The probes of the invention can be moved into close proximity to the site proximate to the target feature using apparatus that is available currently for the positioning of

a scanned probe microscope (SPM).

[0055] Figure 11 illustrates a probe of the third group of embodiments in a system for controlling movement thereof in close proximity to a surface to be worked. A substrate 1110 rests on a movable stage 1112 for initial coarse positioning of the substrate 1110 and optical navigation under a high-NA (numerical aperture) objective lens microscope 1114 to the surface 1120. High-NA optical microscope viewing/imaging allows one to see where tip 1116 is relative to the feature of interest on the substrate, even if the feature of interest is below top surface 1120 (cases when the substrate includes one or more optically transparent layers above the feature of interest). The separation between tip 1116 and surface 1120 is then actively regulated via surface force feedback (e.g., from transducer 1122) and control electronics 1124. Tip 1116 preferably includes a transparent guiding means 1140 coupled to a source 1150 to transmit one or both of the coherent radiation frequencies (e.g., laser beam) to probe apex 1116 for generating the micro-plasma. Alternatively, one or both of the frequencies of coherent radiation may be provided externally to the body of probe 1118 ( e.g., by an illuminating source 1160) using a focused laser beam,

maser beam, beamed radio frequency, electron beam, ion beam, etc. If desired, a biasing voltage may be applied to substrate 1110 by source 1170 for the purpose of accelerating ions from the plasma to surface 1120.

[0056] In a preferred embodiment, a reservoir source of fluid 1128 is coupled through one or more ducts 1130 for supplying the fluid to the surface to be worked on the substrate 1110. Preferably the duct(s) 1130 provide fluid into a channel of micro-tool 1118 such that the location of fluid delivery to substrate 1110 is controlled in connection with the above-described method for positioning tip 1116 proximate to surface 1120. Alternatively, a chemical for promoting a reaction can be supplied to the substrate as a solid component or coating of a solid LCDP type probe 1118, or supplied to surface 1120 as an ambient, or by flow directed towards the desired reaction site.

[0057] If it is desired to induce mechanical milling, preferably a non-reactive gas (e.g., not reactive with the surface to be treated) can be supplied to surface 1120 and ionized locally by probe 1118. The choice of non-reactive gas may depend on the substrate composition; for example, when an oxide layer is to be processed, nitrogen and oxygen can be considered suitable non-reactive gases for such

purpose. Generally, nitrogen, helium or argon are preferred gases.

[0058] Mechanical milling may be performed with or without assistance of a concurrent chemical reaction involving the surface 1120. For example, a highly localized reactive ion beam etch process can be performed, spatially confined by the plasma generated by probe 1118, when both a chemically reactive species and an inert gas are present. Anisotropy and reaction rate can be tuned by adjusting the relative pressures of the chemical reactant and the inert gas, as well as the biasing voltage 1170 applied to substrate 1110.

[0059] It should be understood that the probes and systems of all three groups of embodiments can generally be used to perform the method of the invention. In a preferred implementation of the methods of the invention using probes from the third group of embodiments, removal of reaction products can also be mechanically assisted by the tool, either by intermittent contact of the tip with the substrate or by electrostatic force exerted between tip and sample surface. Doing so increases the rate and anisotropy of the etch in a similar fashion to the mechanical sputter mill component of FIB GAE processes.